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Novel thermal management system using mist cooling for lithium-ion battery packs

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HIGHLIGHTS

- Novel mist cooling system for Li-ion battery module has been developed.
- CFD models have been developed to simulate the performance of mist cooling system.
- Enhanced conventional dry air cooling performance.
- Optimized inlet mist loading faction has been identified.
- Mist cooling system is able to keep the battery variation temperature less than 3 °C.

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ABSTRACT

Thermal management system is crucial for a Lithium-ion battery pack as cycle life, driving range of electric vehicle, usable capacity and safety are heavily dependent on the operating temperature. Optimum operating temperature of Lithium-ion battery pack is about 25–40 °C. Power availability of the battery pack may differ according to the operating temperature. Although air cooling is the simplest and cheapest cooling solution, the cooling capacity is still limited by the low specific heat capacity. This will cause large variation of temperature of cells across the battery pack. In this study, mist cooling is proposed for battery pack thermal management system. Experiments and numerical simulations are conducted to investigate the thermal performance of conventional dry air cooling and mist cooling. Simulation results are then validated with the experimental data. The simulation results show that mist cooling can offer lower and more uniform temperature distribution compared to dry air cooling. Mist cooling with mass flow rate of 5 gs^{-1} and 3% mist loading fraction is sufficient to ensure the surface temperature of the battery module maintained to below 40 °C. Therefore, mist cooling is a potential solution for the thermal management system of Lithium-ion battery pack.

1. Introduction

The growing awareness of environmental issues and limited resources of fossil fuels has generated considerable interest in pursuing an alternative, renewable energy source to overcome the global energy crisis and stringent emission legislation. On top of that, recognizing the physical impacts of fossil fuel use on the environment and climate system, it has become a global agenda to develop promising alternative energy sources, which are environmentally acceptable and technically feasible. Of late, Electric Vehicle (EV) has received a great deal of attention in the industries and research works as one of the rising green transportation technologies to reduce over-reliance on fossil fuel applications in the transportation sectors. Unlike conventional vehicles which are powered by diesel or gasoline fuelled internal combustion engines (ICE), EV runs on electric power source with off-board charging. This feature also distinguishes the EV from the hybrid electric vehicles, in which battery power is employed to supplement the ICE without plugged-in convenience. In view of this, EV is targeted as a promising alternative to providing cleaner and greener means of transportation in the near future before fuel cell technology reaches its maturity.

Battery pack is the primary energy source for EV and performance of

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Nomenclature

A_P	surface area of the droplet, m^2
C_D	drag coefficient
C_p	heat capacity, $J\,kg^{-1}\,K^{-1}$
D_{AB}	mass diffusion coefficient, $m^2\,s^{-1}$
D_h	hydraulic diameter, m
D_P	droplet diameter, m
dU/dT	entropy coefficient
dV	volume of a numerical cell, m^3
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_{fg}	latent heat of evaporation, $J\,kg^{-1}$
h_m	mass transfer coefficient, ms^{-1}
I	current passing through the battery, A
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L	length of the battery module, m
m_v	mass fraction of vapour
m_p	mass of single droplet, kg
m_{p0}	initial droplet mass, kg
$\overline{m}_P$	average droplet mass in the control volume
$\dot{m}_P$	mass flow rate of droplet, $kg\,s^{-1}$
Δm_p	total evaporated water vapour in the one-time step, kg
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
$\dot{q}'''$	volumetric heat source, $W\,m^{-3}$
Re_D	droplet relative Reynolds number
S_m	volumetric mass source, $kg\,m^{-3}\,s^{-1}$
Sc	Schmidt number
Sh	Sherwood number
T	temperature, K
T_b	average temperature of the battery body, K
u	velocity, $m\,s^{-1}$
U	open circuit voltage, V
V_{batt}	battery voltage, V

Greek symbol

μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
ρ	density, $kg\,m^{-3}$
τ	shear stress, Pa

Subscripts

v	evaporated vapour
P	dispersed fluid

the EV is greatly dependent on the operation of the battery pack. Nowadays, Lithium-ion (Li-ion) battery is widely used in the EV battery pack due to its high energy and power density, no memory effect, long cycle life, and fast charging capability [1–2]. However, performance of the battery pack is very sensitive to the working temperature. Ideal working temperature range of the Li-ion battery is between 25 °C and 40 °C [3]. Reducing the battery temperature will increase the battery's internal resistance, and subsequently lessen the energy output from the battery. In contrast, increasing the battery temperature will enhance the battery's degradation rate as well as its impedance and this will result in a shorter battery cycle life. In extreme conditions, high operating temperature may cause irreversible chemical reactions, leading to the generation of thermal runaway [4–6]. Hence, a thermal management system is desired to maintain the operating conditions of the battery pack at optimum levels as well as to ensure safety and reliability of the battery pack.

The main function of the battery pack thermal management system is to maintain the average temperature of the battery cells at their optimum operating temperature window, in which the variation of the individual cell temperature in the battery pack is less than 5 °C [3,7]. The common types of cooling technology used in these Li-ion battery packs include air cooling, liquid cooling, phase change material (PCM) as well as the mix combinations of them [8–13]. Among all these cooling technologies, air cooling technique, particularly with the use of reciprocating flow, has been employed by Mahamud and Park [14] to investigate its feasibility on the battery pack to enhance temperature uniformity and reduce maximum operating temperature. In comparison to the air cooling method with uni-directional flow, reciprocating air cooling method with reciprocating period of 120 s is found to be more effective whereby a 72% reduction in the battery pack's maximum temperature is recorded. Apart from this, it is also observed that the temperature distribution of the battery surface is more uniform when shorter reciprocating period is used. In spite of this, the battery temperature located at the center of the battery pack is always higher as compared to those at both ends. Furthermore, Mi et al. [15] have investigated the thermal performance of the battery pack installed with cooling fin as thermal management system and air is used as a cooling fluid. Finite element analysis results reveal that thermal performance of the battery pack is proportional to the length of the cooling fin. At least 25 mm of cooling fin length is needed to ensure that the battery pack temperature is maintained below the threshold temperature of 40 °C. On the other hand, Vita et al. [16] have used computational fluid dynamic (CFD) simulation to inspect temperature distribution of the Lithium Iron Phosphate battery pack using natural convection, forced air convection and liquid cooling under different C-rates of constant current charging/discharging. A small gap of 2 cm is reserved in between the battery blocks to function as a cooling channel. It is found that the maximum temperature of the battery cell is increased by 10 °C for natural convection, and 8 °C by forced convection using $0.0695\,kg\,m^{-2}\,s^{-1}$ of cooling air. Besides, variation of temperature within the battery pack is more homogeneous for natural convection as compared to forced convection at the end of the discharging/charging process. Meanwhile, for liquid cooling, a counter-flow cold plate is sandwiched in between the battery blocks to dissipate the heat generated. The final temperature of the battery was only increased by 2.5 °C when $239\,L\,h^{-1}\,m^{-2}$ of water flow was used. In view of the benefits of liquid cooling, this technique has been adopted by Basu et al. [17] in their three-dimensional electrochemical thermal modelling work to analyze the liquid cooling thermal management system of 18,650 battery packs. Aluminum sheets are wrapped around the cylindrical cell to extract the heat generated and dissipate them to the cooling channel at both sides of the battery pack. However, the presence of contact resistance between the cells and aluminum sheet has deterred the heat from being conducted effectively to the cooling channel. As a consequence, hybrid PCM with forced air convection battery thermal management system is proposed to improve the performance of the battery pack [18]. Although conventional PCM can reduce sharp rise in battery temperature, heat absorbed by PCM cannot be dissipated efficiently to the surroundings through natural convection. Hence, a forced convection system is applied to dissipate heat accumulated in the PCM. Numerical and experimental results show that at least $3\,ms^{-1}$ of cooling air is required to cool the heated battery pack below 45 °C. Aside from liquid cooling technique, heat pipe based battery pack thermal management system is also a popular choice due to its advantages of compact design, lightweight and high thermal conductivity as compared to liquid cooling [19–20]. This technique has been adopted by Zhao et al. [19] to cool the pouch cells with the use of ultra-thin heat pipes combined with wet cooling, especially for high current operations. For 1 to 3 C-rates of discharge, temperature increment of the cell is less than 4 °C. The variation of temperature across the battery pack is